



## BACKGROUND OF THE INVENTION

## FIELD OF THE INVENTION

5 The invention relates, in general, to the production of spatial, particularly spatially complex structures, i.e. molded bodies, by means of layer build-up methods, as they are also known under the term "powder-based generative rapid prototyping" or "solid free form fabrication" (SFF) methods. Such powder-based generative rapid prototyping methods are known, for example, under the designations 3D laser sintering, 3D laser melting, or 3D  
10 printing.

The invention particularly relates to a powder for use in such a method, as well as to methods for the efficient production of such a powder.

Methods for the production of molded bodies having a complex structure, which are generally computer-controlled, additive, automatic methods, work with bulk of powdered  
15 materials, which are heated in layers, at certain points or in certain regions, to such an extent that a melting or sintering process occurs. For heating, a laser beam, preferably a program-controlled laser beam or, when using metallic powder materials, a high-energy electron beam is used.

In the meantime, various powders have been developed for this technology, whereby  
20 reference can be made, in this regard, particularly to the documents DE 101 22 492 A1, EP 0 968 080 B1, WO 03/106146 A1, or DE 197 47 309 A1, for the sector of plastic powders, or to WO 02/11928, for the sector of metallic powders.

In order to be able to conduct the shaping process without problems, at a high process stability, powder particles that are characterized by particularly good "flow behavior" during  
25 application of the powder layer are required, and this is assured in that the powder particles are configured to be as spherical as possible, with the smoothest possible surface.

Until now, polyamide, particularly a highly cross-linked polyamide, such as PA 11 or PA 12, has particularly proven itself as a material for the method described initially.

However, with this powder material, the spectrum of use of the molded bodies  
30 produced with it is limited. Therefore, various attempts have already been made to modify the powders, in order to improve the mechanical properties of the molded body. One approach was seen in mixing the thermoplastic powder with glass beads or aluminum flakes.

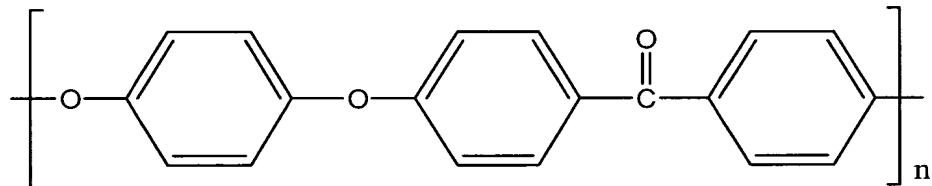
It is true that a good flow capacity is maintained with the glass beads, but the improvements in mechanical properties that can be achieved are limited. It is true that

stiffening of the material is possible (increase in the modulus of elasticity), but it was not possible to significantly increase the tensile strength, and the improvements that could be achieved were obtained at the expense of the material becoming brittle. This problem is even more marked when using aluminum flakes.

5 The invention is therefore based on the task of improving the method for the production of molded bodies by means of selective sintering or melting of powdered materials, in such a manner that while maintaining the fundamental design of the machine, molded bodies having significantly improved mechanical properties can be produced.

This task is accomplished by means of a new powder according to claims 1 and 2, as  
10 well as by means of a method for the production of such powders, according to claims 14, 15,  
20, and/or 25.

According to a first aspect of the invention (claim 1), the essentially spherical powder  
particles are formed by an aromatic polyether ketone plastic, particularly a polyaryl ether  
ketone (PEEK) plastic, having the repetition unit oxy-1,4-phenylene-oxy-1,4-phenylene-  
15 carbonyl-1,4-phenylene according to the following formula:



This linear, aromatic polymer, which is marketed by the Victrex company under the  
20 name "PEEK," is generally semi-crystalline and is characterized by physical properties that  
are far superior to the materials used in SLS methods until now, in every regard. Not only the  
mechanical properties, such as tensile strength and modulus of elasticity, are many times  
better than in the case of conventional PA powders. In addition, the thermal stability of this  
material is so good that the components produced from this material according to the SLS  
25 method can even be used where until now, even fiber-reinforced plastics were not up to the  
job.

The inventors have recognized that this material can be processed to form powder  
particles that are smooth and spherical, to the greatest possible extent, using a suitable  
method, particularly by means of the methods of claims 14, 20, and/or 25, which particles  
30 thereby guarantee a sufficiently good flow capacity of the powder, so that the individual  
layers can be applied with the greatest possible precision.

According to a second aspect of the invention, a powder is made available, having a first component present in the form of essentially spherical powder particles that is formed by a matrix material, and having at least a further component in the form of stiffening and/or reinforcing fibers. In this connection, the matrix material can be a plastic or a metal. Studies 5 have shown that if the volume proportion of the fibers, depending on the fiber length distribution, remains limited, for example to a maximum of 25%, preferably to up to 15%, particularly preferably up to 10%, the flow capacity of the powder can be controlled well. The experimental results show that using PA12 as the matrix material, triple the stiffness and a 50% increase in tensile strength can be achieved with as little as 10 vol.-% fiber proportion 10 (carbon fibers).

To further improve the mechanical properties, the fiber proportion should be increased. According to the invention, the powder with the highest volume proportion of fiber is produced using the production methods according to claims 14, 15, 20, and/or 25, whereby it is possible to embed the fibers into the matrix material, preferably in such a 15 manner that they are essentially completely surrounded by the matrix material. In this manner, the handling of the powder remains essentially uninfluenced by the volume proportion of the fiber material. Using PA12 as the matrix material and using a volume proportion of the carbon fibers of 30%, an increase in tensile strength of 300% and an increased in the modulus of elasticity by a factor of 9 can be achieved, depending on.

20 If a thermoplastic plastic is used as the matrix material, significant improvements in the mechanical properties as compared with the non-reinforced material can be achieved even if flakes are used instead of fibers, as long as their dimensions permit preferably complete embedding into the powder particles. This aspect is explicitly included in the object of the invention.

25 If the matrix material is formed by a plastic material, the fibers are preferably selected from the group of carbon and/or glass fibers.

Fundamentally, the powder can be produced in all the grades that have been processed until now, whereby the powder particles can have an average diameter  $d_{50}$  in the range of 20 to 150, preferably from 40 to 70  $\mu\text{m}$ . The spread of the grain size distribution should be as 30 narrow as possible, so that the flow capacity is not impaired too greatly.

The matrix material can, of course, also be formed by a metallic material. This does not fundamentally change anything with regard to the production methods of the powder particles having embedded fibers, according to claims 15, 20, and/or 25.

A metallic matrix material is preferably combined with fibers from the group of ceramic fibers and boron fibers.

In this case, it is advantageous if the average grain size  $d_{50}$  of the spherical powder particles lies between 10 and 100, preferably between 10 and 80  $\mu\text{m}$ . The value of  $d_{50}$  refers 5 to that dimension of the grain size that is exceeded by 50% of the powder particles, and 50% of the powder particles lie below it.

The fiber length distribution is selected in such a manner that as low a percentage of 10 the fibers as possible projects out of the surface of the particles that are formed during melt-spraying or spray-drying. This can be achieved, for example, in that the average length  $L_{50}$  of the fibers corresponds to maximally the value of the average grain size  $d_{50}$  of the spherical powder particles.

A first advantageous method for the production of a powder, particularly according to 15 one of claims 1 to 13, is the object of claim 14. Using this method, it is possible to produce essentially spherical powder particles, as a function of the process parameters, which can be changed; it is true that these particles are composed of a plurality of smaller particles, but they have a sufficiently spherical and smooth surface so that they can be used in rapid prototyping methods, without problems.

This method can be carried out, equally advantageously, in the presence of a second 20 phase in the form of a stiffening or reinforcing fiber. All liquids that permit a uniform distribution of the micropowder particles and, optionally, of the reinforcing phase, can be used as the liquid phase of the suspension. Another relevant aspect in the selection of the liquid is the property that it vaporizes or evaporates quickly and without leaving a residue.

Preferably, in this method, if the matrix material has been selected from the group of 25 thermoplastics, micropowder having an average grain size  $d_{50}$  between 3 and 10  $\mu\text{m}$ , preferably 5  $\mu\text{m}$  and, optionally, fibers, preferably having an average length  $L_{50}$  of 20 to 150  $\mu\text{m}$ , preferably 40 to 70  $\mu\text{m}$ , are used. The value  $L_{50}$  designates the length that is exceeded by 50% of the fibers, and 50% of the fibers lie below this value.

Claim 17 indicates advantageous dimensions of the particles for metal as the matrix material.

30 An alternative method for the production of the powder according to the invention is the object of claim 20. It is mainly of interest for thermoplastic materials, but can fundamentally be used also for metallic materials. In this connection, the step of cooling is absolutely necessary for thermoplastic materials, so that the material is made brittle to such

an extent that it can be ground. Advantageously, the cooling takes place by means of liquid nitrogen. Other advantageous embodiments of this method are the object of claims 22 to 24.

A third alternative of the production method is so-called melt-spraying according to claim 25, which can also be used for metallic and thermoplastic materials. Important process parameters for adjusting the desired grain size distribution are: temperature of the melt; viscosity and surface tension of the melt; die diameter; speed, volume flow, pressure, and temperature of the gas stream.

Preferably, atomization of the melt takes place in a hot gas jet.

Using the powder according to the invention, which can be produced using a method according to the invention, it is possible to clearly expand the area of application of components or molded parts that have been generated by means of layer build-up methods (powder-based generative rapid prototyping), such as according to SLS (selective laser sintering) or laser melting technology. Using the invention, it is therefore possible, for the first time, to use such a layer build-up method, in practical manner, for the production of hollow molded bodies having interior reinforcements, preferably three-dimensional framework-like reinforcements. This is because until now, the mechanical properties of the material were so low that even with reinforcing structures, it was not possible to use the material in areas that were under thermal and/or mechanical stress.

In the following, the invention will be explained in greater detail, using exemplary embodiments:

The drawing shows:

Figure 1 a fundamental diagram to show the functional principle of the layer build-up method;

Figure 2 the detail II in Figure 1;

Figure 3 a schematic representation of a method for the production of the powder according to a first embodiment;

Figure 4 a schematic view of a powder according to a further embodiment of the invention;

Figure 5 a schematic view of a powder according to a further variant of the invention;

Figure 6 a schematic representation of a method for the production of the powder according to Figure 5, corresponding to one embodiment;

Figure 7 a schematic representation of another method for the production of the powder according to Figure 5;

Figure 8 a schematic view of a cut-out of a component that can be produced using the powder according to the invention; and

Figure 8A the detail VIII in Figure 8.

Figure 1 schematically shows how a component is produced by means of layer build-up methods. It can be seen that successive powder layers 12-1, 12-2, ... 12-n having a thickness S are being applied to a platform 10 that can be lowered into a construction space, step by step. After a layer has been applied, the particles 18 (see Figure 2) are selectively melted in targeted areas, completely or in part, by an energy beam from an energy source 16, whereby the regions 14 indicated with cross-hatching in the figure are formed, which thereby 10 become an integral part of the component being produced. The platform is subsequently lowered by the layer thickness S, whereupon a new powder layer having the layer thickness S is applied. The energy beam passes over a predetermined area once again, whereby the corresponding regions are melted and melded, i.e. joined with the regions in the previous layer that were melted. In this manner, a multi-layer powder block having an embedded 15 molded body of a complex structure is gradually formed. The molded body is removed from the powder block and generally the residual powder that adheres to it or is sintered to it is cleaned away manually.

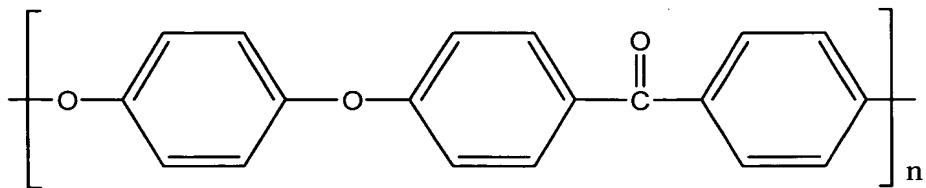
The layer thickness is selected to be between 20 and 300  $\mu\text{m}$ , depending on the area of application, whereby the majority of the powder particles 18 have a grain size D of 20 approximately 1/3 of the layer thickness S, as can be seen in Figure 2.

Conventionally, the powder is formed by a thermoplastic, for example PA 11 or PA 12, whereby the mechanical strength of the molded bodies remains limited, due to the low modulus of elasticity in the range of 1.4 GPa, and the low tensile strength in the range of 40 to 50 MPa.

25 The invention gives different approaches for the production of molded bodies having significantly improved mechanical properties, which will be explained in greater detail in the following:

Embodiment 1:

The powder has a first matrix component that is present in the form of essentially 30 spherical powder particles (18), which is formed by an aromatic polyether ketone plastic, particularly a polyaryl ether ketone (PEEK) plastic, having the repetition unit oxy-1,4-phenylene-oxy-1,4-phenylene-carbonyl-1,4-phenylene of the general formula



5 Such a material can be purchased, for example, under the trade name "PEEK," from the company Victrex Plc. The material properties lie at a tensile strength of more than 90 MPa and a modulus of elasticity in the range of more than 3.5 GPa (according to ISO 527). In addition, this material is characterized by an extremely good temperature stability, so that the molded parts built from it can be used even in areas that are subject to great thermal  
10 stress.

The production of powder particles from this material preferably takes place according to one of the following methods:

15 1. Spray-drying,  
2. Grinding; and  
3. Melt-spraying.

Spray-drying:

20 For this purpose, as can be seen in Figure 3, a suspension is first produced, having a matrix micropowder 22 stirred into a liquid phase, such as ethanol or an ethanol/water mixture 20. The particles of the matrix micropowder 20 have dimensions that lie significantly below the particle size DP of the powder particle 30 to be produced. In this connection, uniform mixing of the phases in the vessel must be assured.

25 The suspension is sprayed through a nozzle, not shown in detail, whereby droplets 32 containing matrix micropowder are formed. The liquid phase 26, specifically the surface tension of this phase, guarantees an essentially spherical shape of the droplets.

Subsequently, for example in a subsequent heating segment, the liquid component 26 of the droplets 32 is vaporized and/or evaporated, leaving essentially spherical agglomerates  
30 30 behind. These agglomerates 30 form the powder particles to be used in the subsequent

layer build-up method. Accordingly, the process parameters of the method are selected in such a manner that the particles are produced in the desired grain size distribution.

Grinding:

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An alternative method consists in that the material, which can be purchased, for example, as a coarse granulate having a grain size of approximately 3 mm, is ground to produce a suitable micropowder.

In this process, the coarse granulate is first cooled to a temperature that lies below the 10 temperature at which the material becomes brittle. Cooling takes place, for example, by means of liquid nitrogen. In this state, the coarse granulate can be ground in a pinned disk mill, for example. The ground powder is finally separated, preferably in an air separator, to obtain a predetermined fraction spectrum.

The method step of grinding can take place with additional cooling.

15 In order for the ground powder to get a sufficiently smooth and preferably spherical surface, it is advantageous to subject the ground material to smoothing treatment, for example by embedding or accumulation of microparticles and/or nanoparticles, such as Aerosil.

Melt-spraying:

20 A third method variant of the production of micropowder made of aromatic polyether ketone, particularly a polyaryl ether ketone, consists in that a melt-spraying method is used.

In this process, the material is melted in a crucible that has a connection to a spray nozzle with which the material is atomized.

25 In this process, small droplets leave the nozzle. Because of the surface tension of the material, these droplets assume an essentially spherical shape. If the droplets are subsequently moved through a cooling segment, they solidify in this spherical shape, so that powder is present in the grade desired for the layer build-up method.

Preferably, hot gas is used for the atomization. The hot gas that is used for spraying, i.e. for atomization of the melted material, is produced by means of a so-called pebble heater.

30 As a rule, a separating step follows the method step of spraying, in order to obtain powder particles in accordance with a predetermined fraction spectrum.

Embodiment 2:

As shown schematically in Figure 4, powder having a first component present in the form of essentially spherical powder particles 118, which is formed by a matrix material, and at least one further component in the form of stiffening and/or reinforcing fibers 140. The matrix component can be formed by a metal or by a thermoplastic plastic.

5 The following experimental example was carried out:

PA12 powder having a grain size distribution with  $d_{50}$  at about 50  $\mu\text{m}$  was mixed with 10 vol.-% carbon fibers of two different types, having an average fiber length  $L_{50}$  of about 70  $\mu\text{m}$  and a fiber thickness of 7  $\mu\text{m}$ . It was possible to process the powder obtained in this way on commercially available rapid prototyping machines, to produce defect-free

10 molded bodies.

It was possible to significantly improve the mechanical properties of the sample body produced on the basis of this powder/fiber mixture, according to the layer build-up method, as compared with a component that did not contain any fibers. Specifically, it was possible to increase the modulus of elasticity to more than 3.8 GPa and the tensile strength to

15 approximately 70 MPa.

These experimental results were compared with results obtained with components that were obtained by means of injection-molding of PA12 mixed with fibers, whereby the fibers that were added to the injection-molding mass were present in the same volume concentration and the same size distribution. The measured results show that the mechanical properties of

20 the components obtained according to the layer build-up method are not inferior, in any regard, to those of the injection-molded parts. In fact, it was actually possible to increase the modulus of elasticity in the case of the sintered body.

Although the proportion of fibers in the micropowder can be varied, depending on the average grain size and its distribution, it generally cannot be raised above 25% without

25 causing problems. In order to nevertheless be able to achieve improved material properties, the third embodiment of the invention is offered.

### Embodiment 3:

According to the third embodiment, which is illustrated schematically in Figure 3, a powder is created that contains significantly higher proportions of fiber, namely above 30 vol.-%, but nevertheless has such a composition that it can be used in a layer build-up method, because of its good flow capacity.

The particular feature is that the fibers 240 are embedded in essentially spherical powder molded bodies 218, which form the matrix material of the component to be produced,

preferably in such a manner that they are essentially completely surrounded by the matrix material, as shown in Figure 5.

For the production of such a powder, the methods described above, i.e. spray-drying, grinding, and melt-spraying, can be used with slight modifications:

5

Spray-drying:

This method is shown schematically in Figure 6. It differs from the method described above, on the basis of Figure 3, only in that not only matrix micropowder 322 but also stiffening or reinforcing fibers 340 are stirred into the liquid phase, such as an ethanol or an 10 ethanol/water mixture 320. The particles of the matrix micropowder 20 have dimensions that lie significantly below the particle size DP of the powder particle 30 to be produced. The fiber lengths are also selected in such a manner that their average length is not greater than the average grain size of the powder particles to be achieved. In this connection, again, uniform mixing of the phases in the vessel must be assured.

15 When spraying the suspension through a nozzle, not shown in detail, droplets 332 that contain matrix micropowder and fiber(s) form. The liquid phase 326, specifically the surface tension of this phase, guarantees an essentially spherical shape of the droplets.

20 If, subsequently, the volatile component 326 of the droplets 332 is vaporized and/or evaporated, again, essentially spherical agglomerates 330 remain behind. These agglomerates 330 form the powder particles to be used in the subsequent layer build-up method. Accordingly, the process parameters are selected in such a manner that the particles are produced in the desired grain size distribution.

Good results can be achieved with the spray-drying if micropowders having an average grain size  $d_{50}$  between 3 and 10  $\mu\text{m}$ , preferably 6  $\mu\text{m}$ , are used.

25 If fibers are stirred in, they should preferably be used at an average length  $L_{50}$  from 20 to 150  $\mu\text{m}$ , preferably 40 to 70  $\mu\text{m}$ .

In the case of a metallic matrix material, the lengths of the fibers should generally be selected to be shorter. An advantageous range for the average fiber length  $L_{50}$  lies between 10 and 100  $\mu\text{m}$ , preferably between 10 and 80  $\mu\text{m}$ .

30 It is advantageous to adjust the process parameters in such a manner that essentially spherical microdroplets having an average diameter  $D_{50}$  of 10 to 70  $\mu\text{m}$  are formed.

The vaporization and/or evaporation step is advantageously carried out while the droplets are being moved through a heating segment.

Grinding:

An alternative method, which is shown schematically in Figure 7, consists in that a material containing fibers, for example carbon fibers 440, which material is present, for example, as a coarse granulate 450 having a grain size or edge length of about 3 mm, is 5 ground to produce a suitable micropowder.

In this process, the coarse granulate 450 is again cooled to a temperature that lies below the temperature at which the material becomes brittle. Cooling takes place, for example, by means of liquid nitrogen. In this state, the coarse granulate can be ground, for example, in a pinned disk mill, indicated as 460. The ground powder is finally separated in a 10 separator 480, preferably in an air separator, in accordance with a predetermined fraction spectrum that is to be achieved. The powder particles to be used are indicated as 430.

In this connection, the method step of grinding can again take place with additional cooling. Also, an optional smoothing process, by means of embedding or accumulation of microparticles and/or nanoparticles, such as Aerosil, can follow.

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Melt-spraying:

The third method embodiment described above, namely so-called melt-spraying, can also be used for the production of powder according to Figure 5.

In contrast to the method described above, the fiber component is stirred into the 20 melted melt of the matrix material.

The embodiments described above allow the processing of both thermoplastic plastic materials and metallic materials.

Different materials can also be mixed.

If the matrix material is formed by a thermoplastic plastic material, the fibers are 25 selected from the group of carbon and/or glass fibers.

The average grain size of the spherical powder particles is fundamentally not supposed to be restricted. Good results with commercially available machines can certainly be achieved if the average grain size  $d_{50}$  of the spherical powder particles lies in the range of 20 to 150, preferably 40 to 70  $\mu\text{m}$ . The flow capacity of such a powder can be further 30 increased by homogenization of the size distribution.

If the matrix material is formed by a metallic material, the fibers are preferably selected from the group of ceramic fibers and boron fibers. In the case of such a powder, the average grain size  $d_{50}$  of the spherical powder particles generally lies at a low value, for example in the range of 10 and 100, preferably 10 to 80  $\mu\text{m}$ .

From the description, it becomes evident that using the powder according to the invention, by using layer build-up methods (powder-based generative rapid prototyping method), such as according to SLS (selective laser sintering) or laser melting technology, it is possible to produce spatial structures, i.e. molded bodies, whose mechanical and/or thermal properties were previously unthinkable.

Thus, the modulus of elasticity of PEEK, if it is reinforced with 10, 20, or 30 vol.-% carbon fibers, which are introduced into the powder particles or mixed with them, according to one of the methods described, can be increased to 7, 13.5, and 22.2 GPa, respectively, while it was possible to raise the tensile strength to 136, 177, and 226 MPa, respectively.

If PA12 is used as the matrix material, an improvement of the mechanical properties occurs as follows, with a fiber proportion of 10, 20, and 30 vol.-%: modulus of elasticity 3.4, 6.6, and 13.9 GPa, respectively; tensile strength 66, 105, and 128 MPa, respectively.

In this way, it is possible, for the first time, as indicated schematically in Figures 8, 8A, to use the layer build-up method for the production of hollow molded bodies 570, having a complex shape, for example multiple curvatures, with interior reinforcements, preferably three-dimensional framework-like reinforcements 572, in practical manner, making it possible to produce components that are not only extremely light, but also can withstand great thermal and mechanical stress.

Of course, deviations from the embodiments described above are possible, without leaving the basic idea of the invention. Thus, subsequent treatment steps of the individual powder production methods can also be used for different methods. The smoothing process to be carried out by means of microbodies can, of course, also be used for the two methods described as alternatives.

The invention therefore creates new powders for use in the production of spatial structures, i.e. molded bodies, using layer build-up methods, as well as methods for their efficient production. The powders have the special feature that they have good flow behavior, for one thing and, at the same time, have such a composition that the molded body that can be produced with the powder, using rapid prototyping, has significantly improved mechanical and/or thermal properties. According to a particularly advantageous embodiment, the powder has a first component that is present in the form of essentially spherical powder particles, which is formed by a matrix material, and at least one further component in the form of stiffening and/or reinforcing fibers, which are preferably embedded in the matrix material.